Report to Congress

Advanced Fuel Cycle Initiative: Objectives, Approach, and Technology Summary

Prepared by

U.S. Department of Energy
Office of Nuclear Energy,
Science, and Technology

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ADVANCED FUEL CYCLE INITIATIVE (AFCI)
REPORT TO CONGRESS
May 2005

EXECUTIVE SUMMARY

The Department of Energy (DOE), Office of Nuclear Energy, Science and Technology (NE) has prepared this report in response to Congressional direction in the Conference Report [to accompany H.R. 2754], Making Appropriations for Energy and Water Development for the Fiscal Year Ending September 30, 2004, and for Other Purposes (Report 108-357) of November 7, 2003 and additional direction in the related Senate Report (Report 108-105) of July 17, 2003

The Conference Report directed the Secretary to:

> Conduct the study, described in more detail in the Senate report, to identify the necessary capacities and time scales for implementation of advanced recycle technologies, and to report to Congress by March 2005 with quantitative goals for the AFCI work.

The Senate report, in turn, directed the Department to:

> …explore new and alternative approaches to provide high confidence that the [reprocessing] options finally chosen are the best for further development. The Department shall also contract for studies to determine the probable extent of uranium reserves and global uranium demand. Based on these studies, and on a range of assumptions about the available capacity of monitored retrievable storage and repositories in the country, the project shall identify time scales on which elements of an advanced fuel cycle must be operational in order to impact national requirements for management of spent fuel. This study should include information to guide Congress in establishing the date by which an advanced recycle facility must be available for performing research on scalable, proliferation resistant, waste efficient, recycle technologies as well as other key facilities supporting future spent fuel management strategies. Based on these studies, the Secretary is directed to report to Congress by March 2005 with quantitative goals for the program including evaluation of future spent fuel inventories, and detailed analysis of the various options to achieve these goals.

This executive summary provides an overview of the results of the requested study and the quantitative goals. The body of this report provides additional detail by addressing each of the specific directions of the Senate report.

The Department conducted a range of studies considering different scenarios of future nuclear energy demand and different spent nuclear fuel management strategies to respond to those demands. These studies resulted in a recommended approach to prudently and flexibly address the primary nuclear fuel cycle issues of environmental impacts, proliferation resistance and uranium resource sustainability. The approach includes introduction of limited recycling with current reactors to begin destruction of weapons-usable nuclear materials in spent fuel, followed by a transitional recycling phase with a mix of current (thermal) and new (fast spectrum) reactors to fundamentally change the nature and reduce the environmental impact of nuclear waste, and ending in a sustained recycling infrastructure based on new reactors using recycled material as their primary fuel. This evolution and the approximate time scales are depicted in Figure ES-1.

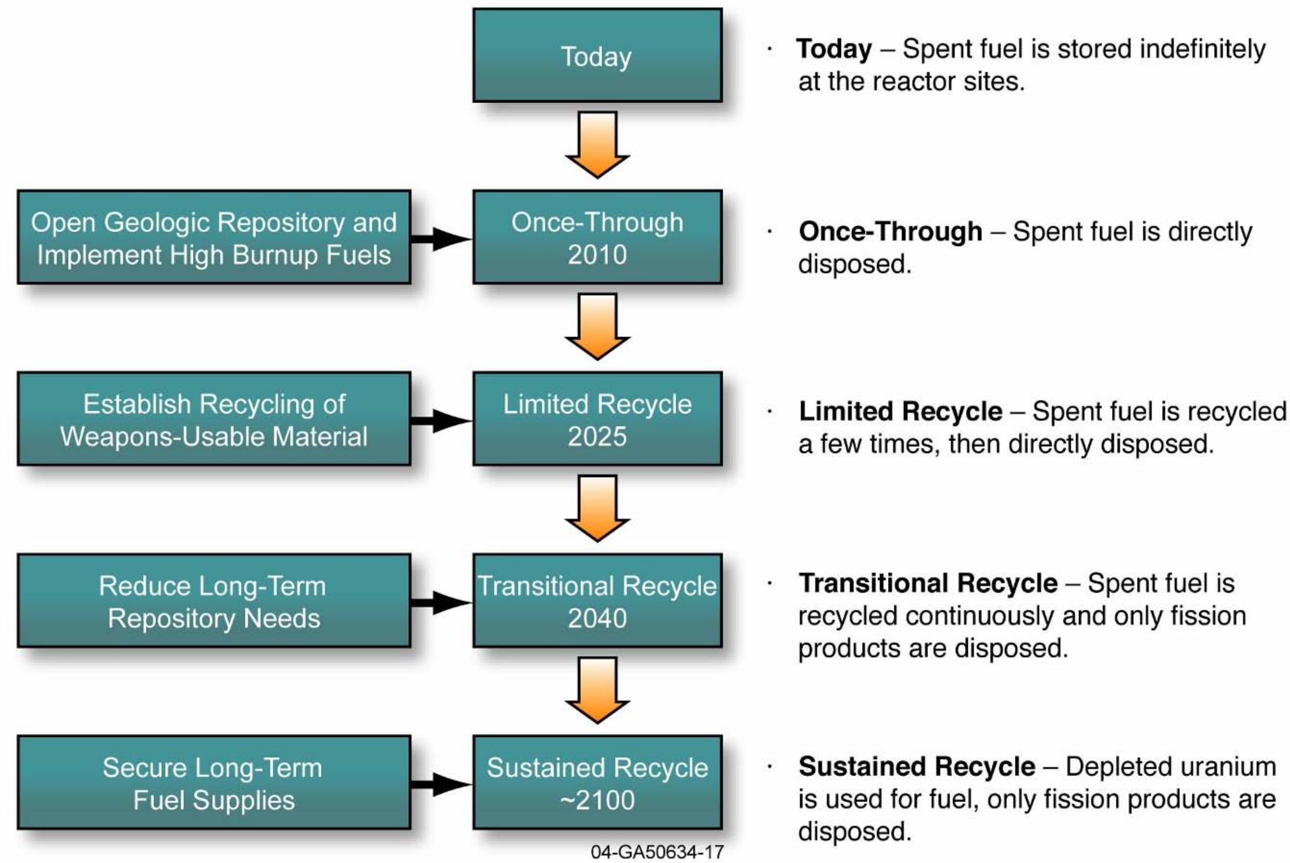

Figure ES-1. Envisioned evolution of the nuclear fuel cycle

By 2100, cumulative discharged spent fuel could expand from the current 50,000 metric tons to as much as 1,400,000 metric tons (under a high-nuclear-growth scenario in which nuclear power increases its share of U.S. energy production by being used to produce hydrogen in addition to electricity.) If additional geologic repositories are to be avoided, the infrastructure required to handle this amount of spent fuel includes the opening of a single geologic repository for high level nuclear waste around 2010, the initiation of commercial-scale recycling in thermal reactors in 2025 and the construction of initial fast spectrum reactors, possibly beginning as early as 2040.

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ADVANCED FUEL CYCLE INITIATIVE
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1 INTRODUCTION

The Department of Energy (DOE), Office of Nuclear Energy, Science and Technology (NE) has prepared this report in response to Congressional direction in the Energy and Water Development Appropriation Bill, 2004 (Report 108-105) of July 17, 2003 and the Conference Report [to accompany H.R. 2754], Making Appropriations for Energy and Water Development for the Fiscal Year Ending September 30, 2004, and for Other Purposes (Report 108-357) of November 7, 2003. The relevant language from these reports is included in Appendix A. These bills charge the Secretary of Energy to submit to Congress a report that provides, among other things, information on new and alternative advanced fuel cycle technologies, quantitative goals for the Advanced Fuel Cycle Initiative (AFCI) program, and time scales on which elements of an advanced fuel cycle must be operational in order to impact national requirements for management of spent nuclear fuel.

This report extracts and addresses each of the bills' individual requirements. The order of presentation addresses AFCI objectives, the approach to meet the objectives, and a summary of the technologies needed.

2 OBJECTIVES AND QUANTITATIVE GOALS

Secure and sustainable energy supplies are critical to continued prosperity. Economic growth both requires and, in turn, feeds rapid growth in energy demand. Nuclear-generated electricity is today's dominant clean, secure source of energy production. To prevent the foreclosure of this valuable technology, the United States must develop new technologies that keep nuclear power cost-competitive while simultaneously offering advantages in the areas of spent fuel management, resource consumption and proliferation-resistance. A mission of the AFCI program is to develop fuel cycle technologies that concurrently will meet the need for an economic and sustained nuclear option while satisfying requirements for a controlled, proliferation-resistant nuclear materials management system.

In keeping with this mission, the strategic goals of the AFCI program are:

- **Develop and make available for industry the separations technology needed to deploy by 2025 a commercial-scale spent fuel treatment facility capable of separating transuranics[1] in a proliferation-resistant manner for their recycle and destruction through transmutation[2].**

- **Develop and make available the fuel cycle technology needed for commercial deployment by 2040 of fast spectrum reactors operating either exclusively as transuranics transmuters or as combined fuel breeders and transmuters.** Actual decisions to deploy fast reactors will, of course, be made by industry in response to market needs.

These strategic goals are the AFCI program's essential contributions to keeping open the option to rely on nuclear power for a portion of the nation's energy needs through the end of the twenty-first century and beyond. Analyses conducted by the Department's AFCI and Generation IV Nuclear Energy Systems (Generation IV) programs suggest that the time-frames identified in these goals are prudent if the nuclear industry is to be able to respond to the challenges that are sure to occur. Some of these analyses will be discussed later in this report.

To help reach its strategic goals, the AFCI program has developed programmatic objectives that guide its research.

Objective 1. Reduce the long-term environmental burden of nuclear energy through more efficient disposal of waste materials.

The first objective of the AFCI program is to limit the environmental impact of nuclear energy production to ensure the sustainability of the nuclear energy option. In particular, the program is working to provide technologies that could eliminate the need for more than one geologic repository for nuclear waste this century. The keys to reducing environmental impacts are the removal and destruction of transuranics (see sidebar, *What are Transuranics?*) and heat-producing fission products. These actions can significantly reduce the heat load that currently limits the technical capacity of the planned repository while also significantly reducing the time-frame over which the waste remains highly radiotoxic.

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1 Transuranics are defined in the sidebar on page 3.

2 Transmutation is defined in the sidebar on page 7.

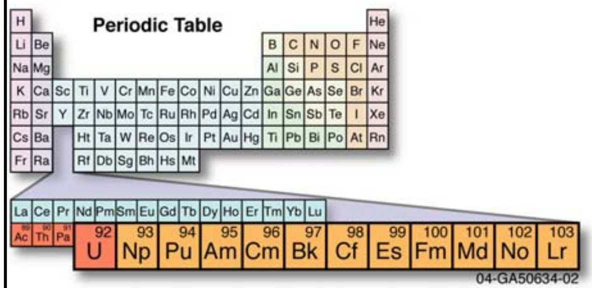
Quantitative environmental goals that support this objective include:

- In the short-term[3], develop and demonstrate fuel cycle technologies and facilities that remove more than 99.5 percent of transuranics from waste destined for geologic disposal and initiate their recycle in existing reactors.

- In the short-term, improve management of the primary heat-producing fission products in spent fuel (cesium and strontium) to reduce geologic repository impacts.

- In the intermediate- and long-terms, enable repeated recycling to reduce disposed transuranics by a factor of more than 100, delaying the need for additional geologic repositories for a century or more, even with growing energy production.

What are Transuranics?



Transuranics are elements in the periodic table with atomic numbers higher than uranium (element 92).

Why do they matter?

Transuranics affect repository performance by dominating long-term heat load and long-term radiotoxicity.

Transuranics and enriched uranium are the only materials of concern for proliferation.

Transuranics can be destroyed while producing extra energy if recycled in nuclear reactors.

The primary transuranics of interest to the AFCI program are neptunium (Np), plutonium (Pu), americium (Am) and curium (Cm).

- In the intermediate- and long-terms, reduce the long-lived radiation dose sources by a factor of 10 and radiotoxicity by a factor of 100, simplifying the design of a waste isolation system.

Objective 2. Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for spent fuel management.

The second objective of the program is to reduce the proliferation potential associated with the weapons-usable materials inherent in spent fuel. This includes both reductions in these materials in storage and in waste streams as well as improvements in monitoring and instrumentation during spent fuel processing and fabrication of recycled fuels. An important part of this objective is the development of more proliferation-resistant recycling technologies that could be adopted worldwide.

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3 For purposes of the AFCI goals in this report, "short-term" refers to the period through 2025, when the program recommends the need for a commercially-deployed spent fuel treatment facility. "Intermediate-term" refers to the period from 2025 until the commercial availability of Generation IV fast spectrum reactors, projected to be about 2040. "Long-term" refers to the time after several of these fast reactors have been built.

Quantitative proliferation resistance goals that support this objective include:

- In the short-term, develop fuel cycle technologies that enhance the use of intrinsic[4] proliferation barriers.
- In the short-term, demonstrate the capability to eliminate more than 99.5 percent of transuranic weapons-usable materials from waste streams destined for direct disposal by destroying these materials through recycling.
- In the long-term, stabilize the inventory of weapons-usable material in storage by consuming it for sustained energy production.

Objective 3. Enhance energy security by extracting energy recoverable in spent fuel and depleted uranium, ensuring that uranium resources do not become a limiting resource for nuclear power.

The third objective is to achieve energy security by guaranteeing a long-term stable fuel supply for nuclear energy. Currently, more than 99 percent of the potential energy in mined uranium ends up in waste streams. Converting this waste liability into an energy asset would provide enough fuel to meet all current domestic electricity needs for 1,000 years. However, current commercial reactors are not capable of performing the conversions necessary to enable the full use of recycled material. Instead, Generation IV fast spectrum reactors will be needed.

Quantitative energy security goals that support this objective include:

- In the short-term, develop the technologies needed to extend nuclear fuel supplies by up to 15 percent by recycling the fissile material in spent nuclear fuel.

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4 "Intrinsic" proliferation resistance features, as defined in the International Atomic Energy Agency Department of Safeguards STR-332, Proliferation Resistance Fundamentals for Future Nuclear Energy Systems, include (but are not limited to) technical features that:

- Reduce the attractiveness for nuclear weapons programs of nuclear material during production, use, transport, storage and disposal;
- Prevent or inhibit the diversion of nuclear material;
- Prevent or inhibit the undeclared production of direct-use material; and
- Facilitate verification, including continuity of knowledge.
- By contrast, examples of "Extrinsic Measures" as defined in STR-332 include:
- States' commitments, obligations and policies with regard to nuclear non-proliferation and disarmament;
- Agreements between exporting and importing states that nuclear energy systems would be used only for agreed purposes and subject to agreed limitations;
- Commercial, legal or institutional arrangements that control access to nuclear material and nuclear energy systems;
- Application of IAEA verification and, as appropriate, regional, bilateral and national measures to ensure that states and facilities comply with non-proliferation or peaceful-use undertakings; and
- Legal and/or institutional arrangements to address violations of nuclear non-proliferation or peaceful-use undertakings.

- In the long-term, extend nuclear fuel resources more than 50-fold by recycling uranium in spent fuel and depleted uranium, thereby converting current wastes into energy assets.

Objective 4. Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system.

The previous three objectives are the planned outcomes of the AFCI program. In addition to these outcome objectives and quantitative goals, the program has also established an operational objective and goals related to safety and economics. While an advanced fuel cycle may provide many benefits in the areas of environmental sustainability, proliferation resistance and energy security, the safety and economics of the related facilities and operations must be comparable to or better than those now in place.

The AFCI outcome goals will convert spent fuel from a liability to an asset. Once sufficient reprocessing capacity is in operation, spent fuel can be removed from extended storage for treatment.

Safety/economics goals that support this objective include:

- At all times, ensure that advanced fuel cycle technologies cause no significant decrease in the economic competitiveness of nuclear electricity.

- At all times, maintain excellent safety performance of nuclear fuel cycle facilities and operations.

- For the long-term, improve spent fuel management to reduce on-site storage at nuclear power plants.

3 TECHNICAL APPROACHES AND ANALYSES

In developing the objectives in Section 2, the AFCI program evaluated potential spent fuel inventories and performed analyses of technical options. The program considered a range of scenarios for domestic nuclear energy through the end of the 21st century:

- Existing License Completion – Nuclear plants are retired at the end of their current licenses and no new plants are built

- Extended License Completion – Nuclear plants are retired after 60 years (one license extension) and no new plants are built

- Continuing Level Energy Generation – Replacement plants are built as current plants retire, but no additional capacity is added (no growth)

- Continuing Market Share Generation – Replacement plants and additional plants are built to maintain nuclear energy's 20 percent electricity market share. Total capacity grows at the same rate as electricity demand (1.8 percent growth). This will be the reference case for this report.

- Growing Market Share Generation – Nuclear market share grows, both for electricity and for hydrogen production (3.2 percent growth).

With current reactor and fuel technologies and no recycling, these scenarios will result in the cumulative spent fuel inventories through the year 2100 shown in Table 1:

Table 1. Cumulative spent fuel inventories through the year 2100 under various nuclear futures

Nuclear Futures	Existing License Completion	Extended License Completion	Continuing Level Energy Generation	Continuing Market Share Generation	Growing Market Share Generation
Cumulative discharged fuel in the year 2100 (metric ton)	100,000	120,000	250,000	600,000	1,400,000
	Existing Reactors Only		Existing and New Reactors		

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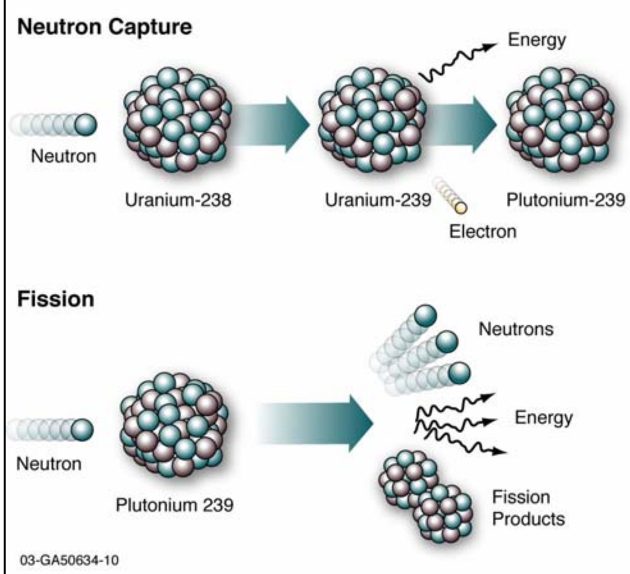
A series of analyses were conducted to determine the strategies and technologies needed to meet the AFCI objectives and quantitative goals for these scenarios. These analyses considered the range of potential nuclear futures, the existing commercial infrastructure and spent fuel inventories, planned government facilities such as the geologic repository, and new technologies in development for both advanced fuel treatment and recycle and advanced reactors.

The analyses indicate AFCI objectives can only be met by significantly improving the management of transuranics in the fuel cycle. Transuranics are the primary contributors to long-term environmental issues. Further, transuranics and enriched uranium are the only materials of concern for proliferation. Transuranics also include the only fissile materials that can be generated from uranium to extend fuel resources.

AFCI strategies for transuranics management in the fuel cycle include methods to modify their production or enhance their destruction via transmutation (see sidebar, *What is Transmutation?*), fundamentally changing the elemental composition of nuclear waste. Transuranics are produced by transmutation (neutron capture) in the reactor core and are destroyed either by additional transmutation (fission) or radioactive decay. Many transuranics decay very slowly, so transmutation is the preferred destruction method.

What is Transmutation?



Transmutation is the conversion of one isotope into another by changing its structure.

To help meet the AFCI environmental objective, the management of the primary heat producing fission products, namely cesium and strontium, should also be improved. The AFCI approach is to segregate these materials from other wastes to optimize their storage and disposal. The fission products technetium and iodine should also be addressed to help reduce repository peak dose. AFCI is developing improved waste forms to immobilize these materials while also investigating destruction through transmutation.

To meet the AFCI fuel cycle management, economics, and safety objectives, fuel cycle facility designs and capacities must be optimized. The AFCI approach includes design, process and control improvements to reduce the size of facilities while increasing their operating capacities.

3.1 Transuranics Management Strategy

The AFCI has identified a transmutation approach that uses a staged evolution of the nuclear fuel cycle to optimize transuranics management and meet the program's objectives. The evolutionary stages are depicted graphically in Figure 1.

The following subsections explain each of the stages in more detail. A flow diagram (Figures 2-5, respectively) graphically represents each stage. The section in each flow diagram that is delineated by a dotted line identifies what has changed from one stage to the next, including new facilities needed to complete the stage of the fuel cycle under discussion.

The concept of evolutionary fuel cycle stages captures several attributes. First, each stage provides a potential off-ramp; unless circumstances require, there is no compulsion to pursue fuel cycle technology all the way through to Sustained Recycle. Second, the succession of stages represents a logical and practical technological progression; although skipping a stage may be possible, any advanced stage will require some technology from each of the earlier stages. Finally, each successive stage offers greater benefits to the geologic repository; the greater the growth of U.S. nuclear power, the farther along the evolutionary track we will have to progress to avoid adding repository capacity this century.

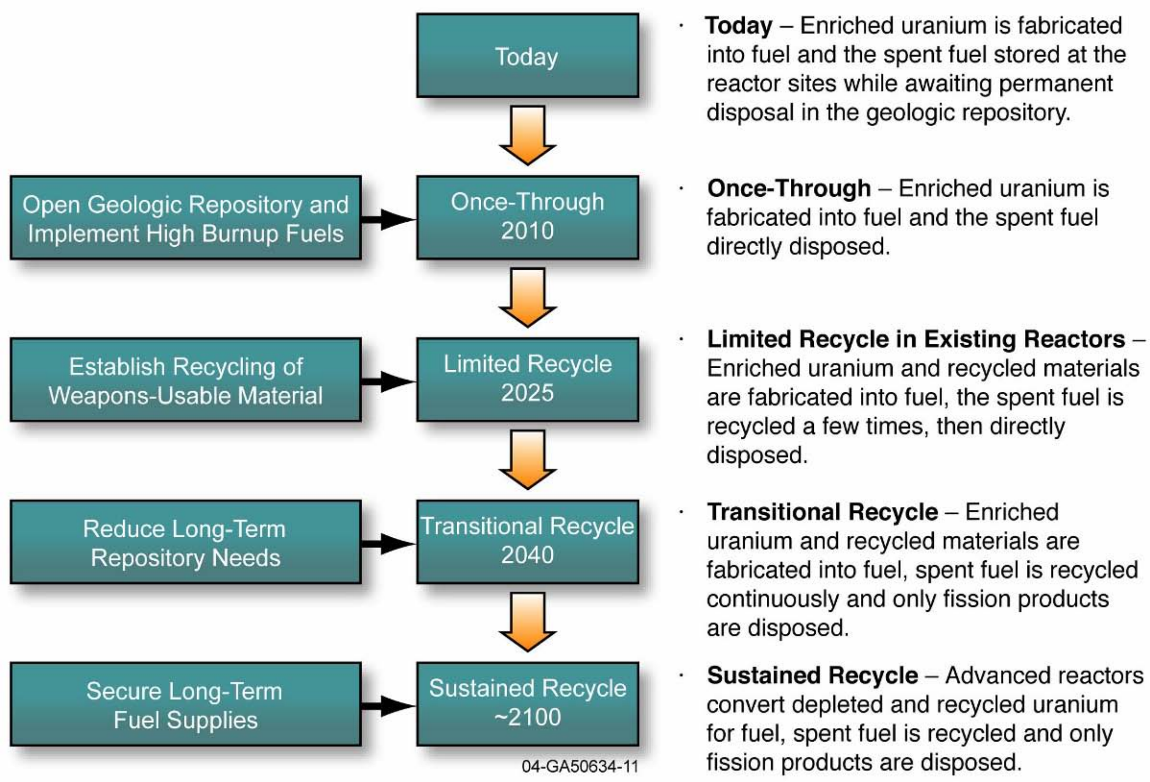


Figure 1. Envisioned evolution of the nuclear fuel cycle

Once-Through

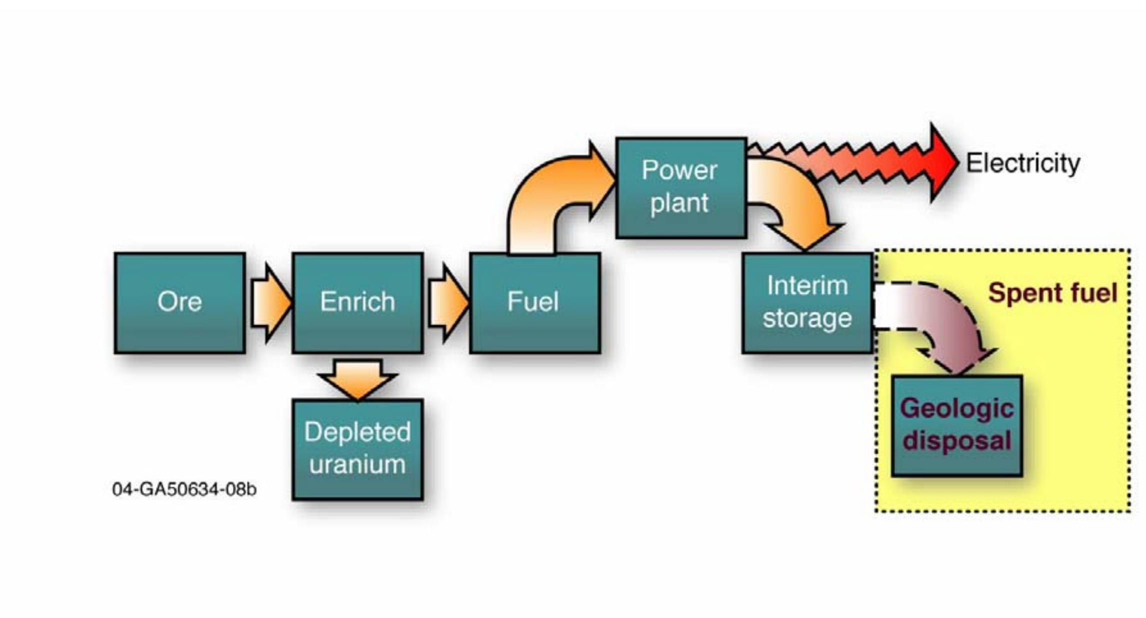


Figure 2. Once-Through Stage

Today the United States is in the process of developing a deep geologic spent fuel repository. In the meantime, spent fuel is stored at 64 reactor sites as it accumulates from 103 currently-operating commercial reactors in 31 states[5].

Opening of the geologic repository is necessary to fully implement the Once-Through fuel cycle. The primary strategy to enhance transuranics management in the Once-Through fuel cycle is to increase the amount of energy produced per unit of spent fuel produced. This is achieved by increasing transmutation of uranium in the reactor to produce additional fissile material, allowing the fuel to "burn" longer before becoming spent.

Industry is working to increase burnup in existing reactors by an additional 20 to 30 percent. AFCI is developing fuels for new reactors that could double burnup. With this "ultra-high" burnup, residual transuranics are reduced by up to 25 percent and concentrated in a smaller amount of spent fuel.

Limited Recycle

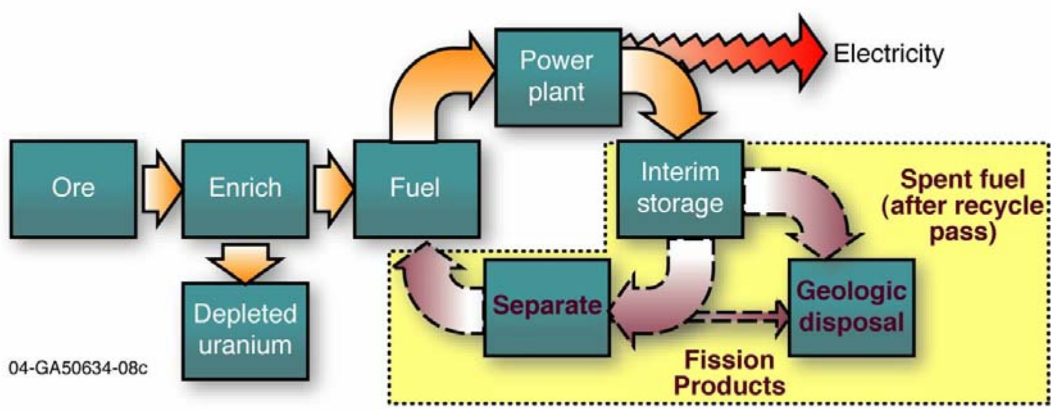


Figure 3. Limited Recycle Stage

In Limited Recycle, transuranics destruction is improved by recovering the transuranics from the spent fuel and recycling some of them back through operating light water reactors (LWR) or advanced LWRs and Generation IV thermal reactors if built in the near- or intermediate-term. This allows direct destruction of fissile transuranics and transmutation of non-fissile transuranics

5 The first number in parentheses indicates the number of currently-operating commercial reactors in each state; the second number the total nuclear capacity in that state by megawatts electric (MWe): Alabama (5; 4,966), Arizona (3; 3,733), Arkansas (2; 1,776), California (4; 4,324), Connecticut (2; 2,005), Florida (5; 3,906), Georgia (4; 4,023), Illinois (11; 11,405), Iowa (1; 566), Kansas (1; 1,170), Louisiana (2; 2,071), Maryland (2; 1,685), Massachusetts (1; 690), Michigan (4; 3,938), Minnesota (3; 1,646), Mississippi (1; 1,231), Missouri (1; 1,143), Nebraska (2; 1,234), New Hampshire (1; 1,161), New Jersey (3; 3,875), New York (6; 5,049), North Carolina (5; 4,731), Ohio (2; 2,111), Pennsylvania (9; 9,127), South Carolina (7; 6,492), Tennessee (3; 3,410), Texas (4; 4,737), Vermont (1; 506), Virginia (4; 3,467), Washington (1; 1,108) and Wisconsin (3; 1,510). Source: U.S. Department of Energy/Energy Information Administration.

into fissile transuranics. Those transuranics not recycled in thermal reactors would be stored for future destruction in fast reactors or permanently disposed in a repository. The AFCI is investigating several approaches to Limited Recycle involving different mixes of transuranics and different levels of uranium in the recycled fuel. Spent fuel treatment and remote fuel fabrication facilities are necessary to transition from Once-Through to Limited Recycling.

Two factors limit the recycle. First, the fissile material can be used up. This happens in one or two cycles for uranium-free fuels, resulting in destruction of more than 90 percent of the fissile transuranics while leaving the majority of the non-fissile transuranics as residuals for disposal. Second, in current reactors curium builds up with each cycle, increasing radiation levels in both the spent fuel and recycled fuel. The high radiation levels require additional shielding during shipment, processing, and recycled fuel fabrication.

Analysis indicates that Limited Recycle can increase the repository capacity to store high-level waste by a factor of two-to-three, providing sufficient improvement in the management of transuranics to meet the near-term goals of the AFCI environmental and energy security objectives. It is insufficient to meet longer-term goals because significant transuranics remain to be disposed after the final cycle. Limited Recycle could be employed for a few decades while Generation IV fast reactors needed for the next stage of fuel cycle evolution are developed and deployed.

<u>Transitional Recycle</u>

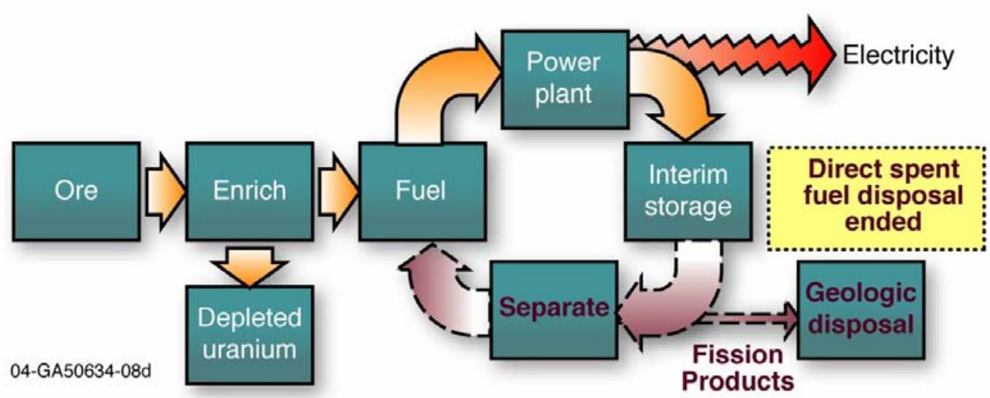


Figure 4. Transitional Recycle Stage

Transitional Recycle represents an extended period when the commercial reactor infrastructure transitions from current Generation II reactors to new Generation IV reactors. In Transitional Recycle, all transuranics are recycled repeatedly until they are destroyed. The Transitional Recycle approach includes a combination of conventional thermal reactors and Generation IV fast reactors to optimize transuranics destruction. Fast reactors use high-energy “fast” neutrons that are more likely to fission transuranics. To prevent buildup, the higher transuranics, such as curium, are recycled into the fast reactor fuel. The fast reactors are configured to consume the residual transuranics. The AFCI program is also investigating methods to achieve repeated recycle and the associated environmental benefits by initially using only conventional thermal reactors.

Transitional Recycle supports both the short-term and long-term environmental and proliferation resistance goals of the AFCI program objectives. Major changes in the nuclear fleet composition are required to complete Transitional Recycle and move on to Sustained Recycle. Thus, an extended transition period including recycle in existing reactors is envisioned to allow gradual introduction of the Generation IV fast reactors for transmutation. To achieve the long-term environmental and proliferation resistance goals, sufficient transmutation technology must be employed by mid-century to enable repeated recycle and avoid geologic disposal of the Limited Recycle spent fuel.

Sustained Recycle

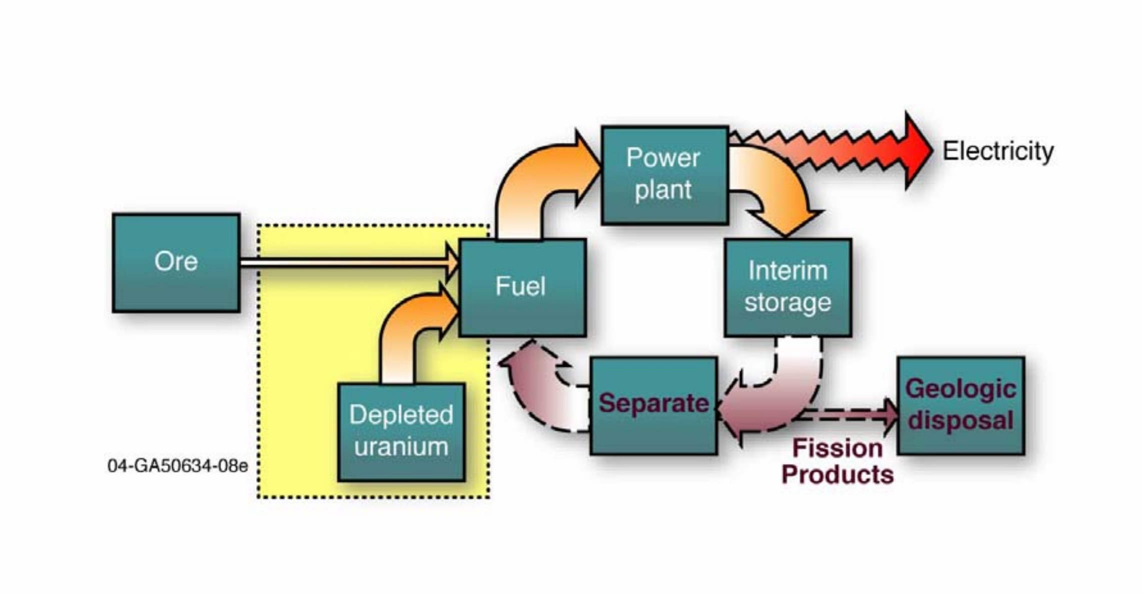


Figure 5. Sustained Recycle Stage

Sustained Recycle is the final evolution of the fuel cycle. This approach uses the same technologies as Transitional Recycle, but relies on a much higher percentage of fast reactors acting as breeders to create more fissile material than they consume. The fast reactors will burn transuranics as their primary fuel while also transmuting natural or recycled uranium to produce more fuel. Through transmutation, Sustained Recycle will be capable of fully using the energy potential of uranium[6]. By directly using natural, depleted, and recycled uranium, Sustained Recycle would also eliminate the need for uranium enrichment, thus enhancing nonproliferation efforts.

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6 The United States currently produces around 450 gigawatt-years of electricity annually from all sources. Commercial spent fuel now in interim storage contains 50,000 metric tons of uranium. Assuming one metric ton of uranium can produce approximately one gigawatt-year of electricity (if fully consumed), 50,000 metric tons of uranium is equivalent to more than 100 years of domestic total electricity generation. The United States is currently storing an additional 470,000 metric tons of depleted uranium (from which energy is recovered by transmuting its U_{238}), sufficient for 1,000 years of electricity generation at current rates.

This approach would only be needed when natural uranium resources become limiting, which is not expected to occur this century (See Section 5 on uranium supply). The technologies and infrastructure demonstrated in Transitional Recycle would enable a future transition to Sustained Recycle to ensure long-term energy security.

3.2 Fission Products Strategy

Two classes of fission products are addressed by the AFCI. The first are rapidly decaying materials that are the major contributors to repository near-term decay heat loads. The second are slow-decaying materials that contribute to long-term radiotoxicity and the predicted peak dose of the repository.

The technologies for dealing with fission products are incorporated in the fuel cycle stages described in 3.1, above. Although the AFCI program is assessing destruction of certain fission products, such as technetium and iodine, through transmutation, greater R&D emphasis is being placed on chemical separations and waste form development, both discussed more fully in 6.1, below.

Cesium and strontium are the primary sources of decay heat in the geologic repository before it is closed. AFCI is developing the capability to separate cesium and strontium from the other fission products so they could be managed separately. Several approaches are being assessed, including storing the material separately until it finishes decay (about 300 years) and direct disposal in a segregated portion of the repository.

Technetium and iodine are the two slow-decaying fission products that contribute to radiotoxicity and peak dose in the long term. The AFCI is assessing enhanced waste forms for these materials that would decrease their rate of release to the environment as a means of reducing their contribution to peak dose.

3.3 Summary of Fuel Cycle Strategies versus AFCI Goals

This subsection summarizes the progress in meeting AFCI goals gained by the implementation of each fuel cycle strategy. The information is based on modeling techniques that simulate transmutation results of several fuel types in both current and advanced nuclear reactors. Fuels considered included standard and ultra-high burnup light water reactor fuels, mixed oxide fuels that include a range of transuranics, inert matrix transuranics fuels that contain no uranium, and new fuels for both thermal and fast spectrum reactors.

Understanding the contribution of each fuel cycle strategy toward achieving AFCI Objectives and Quantitative Goals is the primary focus of AFCI research and development. It is impossible to capture fully the program's rapidly-expanding state of knowledge in a single, simple chart or matrix. Nevertheless, the AFCI program attempts to do this in each year's *Advanced Fuel Cycle Initiative (AFCI) Comparison Report.* In four matrices that comprise the heart of that report, the Nuclear Fuel Cycle Stages identified in Figure 1, along with their most promising associated technologies, will be evaluated according to their contributions to the four major AFCI objectives. Both this report and the FY 2005 *Comparison Report* will be posted on the Office of Nuclear Energy, Science and Technology website at www.nuclear.gov.

3.3.1 Environmental Goals

Table 2 shows the impact of the fuel cycle strategies on limiting the number of geologic repositories needed in this century. Introduction of one or more advanced nuclear fuel cycles may eliminate or significantly postpone the technical need for additional repositories. The greater the number of new nuclear plants in operation, the further along the "evolutionary scale" (Figure 1) fuel cycle technology must proceed in order to avoid additional repositories.

Note in Table 2 that recycling is not considered a viable option for nuclear futures that do not involve new reactors. This is because all recycle strategies require the continued availability of reactors to use the recycled fuel. In the nuclear futures with no new reactors, all nuclear reactors would be retired by mid-century.

Table 2. Impact of different fuel cycle strategies on eventual repository needs under different nuclear futures through the year 2100.

Nuclear Futures		Existing License Completion	Extended License Completion	Continuing Level Energy Generation	Continuing Market Share Generation	Growing Market Share Generation
Cumulative discharged fuel in the year 2100 (metric ton)		100,000	120,000	250,000	600,000	1,400,000
		Existing Reactors Only		Existing and New Reactors		
Fuel Management Approach		Number of Repositories Needed at 70,000 Metric Ton Each				
No Recycle	Once-Through	2	2	4	9	20
No Recycle	Once-Through, High Burnup Fuels	2	2	3	7	17
Reprocess & Recycle	Limited Recycle, High Burnup Fuels	Recycle not Recommended		2	5	10
Reprocess & Recycle	Transitional and Sustained Recycle			1	1	1

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Figure 6 shows the impact on long-term radiotoxicity. Conventional spent fuel radiotoxicity remains above the level of the original source material (uranium ore) for about 300,000 years. This long duration radiotoxicity derives almost completely from transuranics in the waste. By transmuting these transuranics, the radiotoxicity for the Transitional Recycle and Sustained Recycle strategies falls below the uranium ore level after several hundred years. By contrast, while the Limited Recycle approach begins the treatment and recycle process, it produces little improvement over the Once-Through case due to only partial consumption of the transuranics.

In summary, the Once-Through and Limited Recycle strategies do not meet the environmental goals while both Transitional Recycle and Sustained Recycle do meet them.

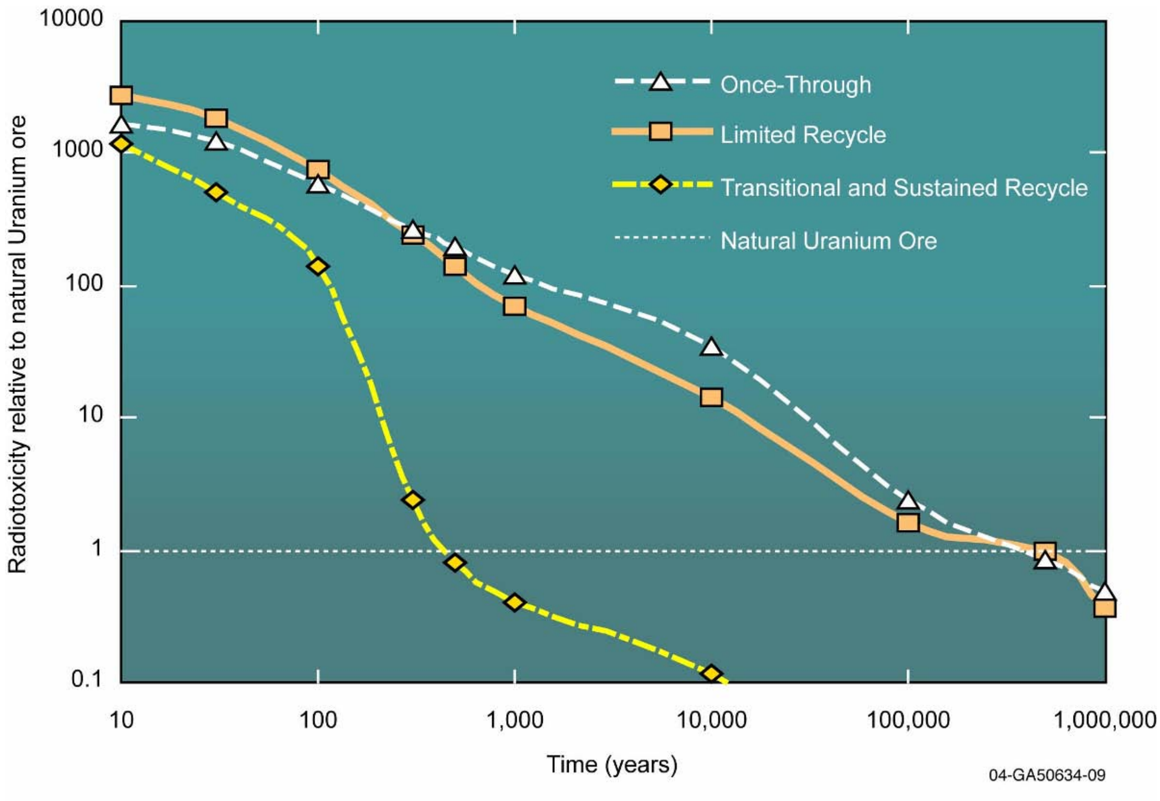

Figure 6. Radiotoxicity for Once-Through, Limited Recycle, Transitional Recycle and Sustained Recycle

3.3.2 Proliferation Resistance Goals

Proliferation concerns for nuclear recycle arise from the need to separate transuranic elements from other components of the spent fuel to achieve this recycle. This results in some products with reduced radiation barriers (compared to spent fuel) that may be attractive targets for material diversion. Therefore, AFCI technologies are being developed for diversion-resistant management of key materials within more fully-closed fuel cycles. Separations technologies that maintain intrinsic barriers (e.g., unattractive material composition, high radiation levels, high heat generation and advanced monitoring and safeguards technologies) are being researched. Advanced monitoring and safeguards technologies are also being included directly into separations, recycle fuel fabrication, and reactor system designs to enhance material tracking and security. These technologies will be developed and demonstrated as larger-scale research capabilities become available. The results of this testing as well as the technologies themselves will be made available to the international community. It may be possible to incorporate these developments in an international convention that would establish new consensus standards for safeguarding nuclear fuel cycle facilities.

The key material for consideration for material diversion is the plutonium that is produced from uranium fuel in a reactor and is present in conventional spent fuel. This plutonium is recycled and transmuted in all advanced fuel cycle strategies. All recycle strategies would reduce the plutonium inventory compared to the Once-Through fuel cycle. This behavior is illustrated in

Figure 7. For this analysis, the bulk of the nuclear power generation continues to be conventional reactors with enriched uranium fuel (producing plutonium), offset by plutonium destruction in the recycle fuels. Thus, the analyses only extend from Once-Through to Transitional Recycle. A more aggressive implementation of fast spectrum reactor technology in Sustained Recycle could be employed to stabilize or decrease the plutonium inventory.

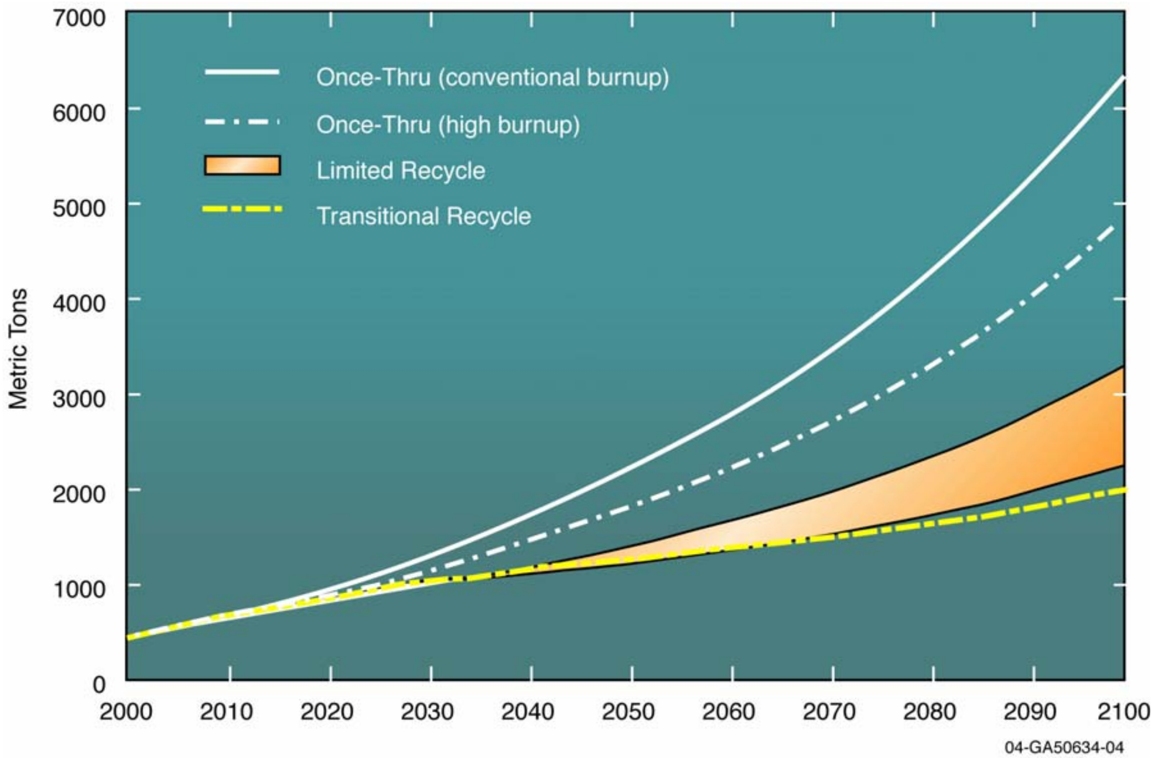

Figure 7. Plutonium inventory for Once-Through, Limited Recycle and Transitional Recycle strategies

In summary, Limited Recycle and Transitional Recycle achieve the short-term proliferation resistance goals, including demonstration of advanced monitoring and safeguards technologies, removal of weapons-usable materials from disposal streams and significant progress in reducing weapons-usable materials in stored spent fuel. Sustained Recycle also meets the long-term goal.

3.3.3 Energy Security Goals

The Once-Through fuel cycle extracts less than one percent of the energy content of natural uranium. Even with ultra-high burnup, Once-Through uranium resource requirements will be similar because additional uranium enrichment is required. In contrast, employing recycle of the transuranics reduces uranium resource requirements because of power production from the recycle fuel. For the Limited Recycle and Transitional Recycle approaches, a modest improvement of about 15 percent in the resource consumption is observed, corresponding to the fraction of overall power capacity generated by the recycle fuels.

To meet the AFCI energy security goals, not only must transuranics be recycled but also both uranium in spent fuel and depleted uranium left over from enrichment must be converted into fuel. Generation IV fast spectrum reactor technologies are required. In small numbers, these fast reactors are used in the Transitional Recycle strategy to burn transuranics. However, the same reactors could be converted to a breeder configuration by adding non-fuel depleted uranium to the reactors. This will allow the transmutation of the uranium into usable fuel. To achieve a sustained rate of fuel production, most reactors will need to be fast reactors. Sustained Recycle will allow significant extended energy production with no uranium enrichment requirements, until the very large depleted uranium reserves are consumed.

It should be noted that Sustained Recycle requires a major evolution of the commercial reactor infrastructure that may require many decades to occur based only on market economics. The timing of this shift is discussed in more detail in Section 5.

In summary, only the Sustained Recycle strategy meets Energy Security goals (see Figure 8).

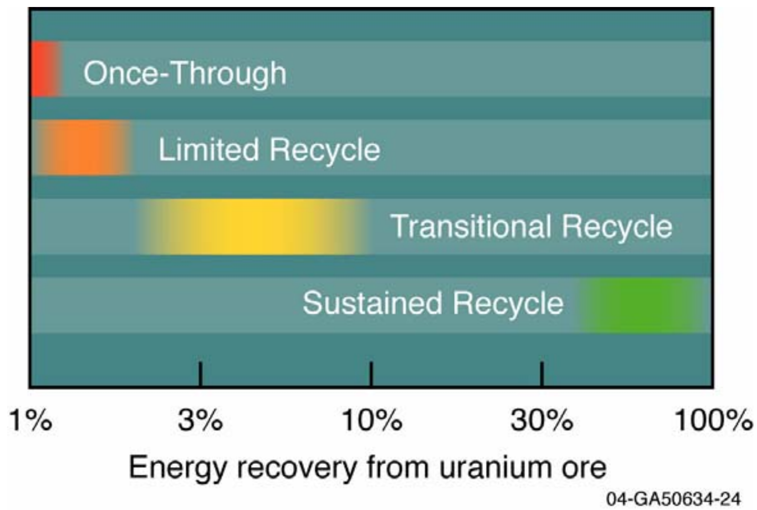

Figure 8. Energy recovery rates from uranium ore for the different fuel cycle stages

4 TIMING ANALYSIS

Congress asked the Department to identify time scales on which elements of an advanced fuel cycle must be operational in order to impact national requirements for management of spent fuel. There is no single answer to this question. While time scales are dependent on developments in the marketplace, the government has options on how to respond to market developments. The approach recommended is to foreclose no feasible option while completing the research and development to identify the most promising course(s) of action.

4.1 Geologic Repositories

Referring back to Table 2, five nuclear futures were considered in the preparation of this report. If existing U.S. nuclear power plants operate to the end of their current licenses or extend their licenses, but no new plants are commissioned, a single geologic repository alone could be sufficient for all spent nuclear fuel, if used to its full technical capacity.

For these two cases, reprocessing and recycling is not recommended. The only new capability that must become operational is the geologic repository. Given the existing 50,000 metric ton backlog of spent fuel, the repository is needed as soon as practical.

Once new nuclear capacity is introduced (represented by the three cases to the right of the heavy vertical line in Table 2), the government has two primary options. Projections suggest that adhering to a Once-Through fuel cycle will require siting, construction and operation of multiple repositories to store the spent fuel accumulated through the end of the century. Under this option, ultra-high burnup fuels lessen the number of repositories needed. Therefore, completion of ultra-high burnup fuels development is recommended as soon as practical (approximately 2010). The other option is to begin reprocessing and recycle of spent fuel.

4.2 Reprocessing Capabilities

The reprocessing and recycle of spent fuel will require the deployment by industry of one or more fuel reprocessing and recycled fuel fabrication facilities. AFCI analyses suggest that industry would need to deploy these commercial-scale facilities, employing advanced separations and fabrication technologies and nonproliferation safeguards, by 2025 if they are to be ready for future fuel cycle, reactor and repository developments. Analyses were conducted for the continuing market share case (1.8 percent annual nuclear growth) to determine the impact of delays in opening this facility. A ten year delay from 2025 to 2035 would increase temporary spent fuel storage requirements by between 15,000 and 30,000 metric tons (depending on whether high burnup fuels are in use). The delay also would require more or larger facilities to be constructed to catch up with the larger backlog.

Analyses further suggest that the capacity of the first commercial-scale reprocessing facility should be 2,500 to 3,000 metric tons per year. Multiple reprocessing facilities would be needed over the course of the century depending on nuclear growth rates. With a 40-year design life, each facility would need to be capable of processing 100,000 to 120,000 metric tons of spent fuel. Under the continuing level energy generation case (zero growth), two such facilities would be required.

4.3 Fast Spectrum Reactors

Once recycling is started, the evolution to Transitional Recycling should occur within ten-to-twenty years. This would preclude the need for direct spent fuel disposal in the geologic repository (though the repository would still be needed for waste disposal) and maximize environmental benefits.

Most Transitional Recycle approaches being investigated by the AFCI program include a small percentage of fast spectrum reactors configured to burn transuranics. Advanced fast reactors are being developed as part of the Generation IV program and are projected to be ready for initial demonstration in approximately 2030, with commercial deployment possibly by 2040.

Several fast reactors may need to be constructed by utilities to enable the repeated recycling that is central to the Transitional Recycle stage. The AFCI program estimates that fewer than twenty percent of operating reactors would need to be fast reactors to fully support repeated recycling. In the interim, some curium and americium from spent fuel could be stored until there is sufficient fast reactor capacity for their destruction. As Transitional Recycle continues, the percentage of fast reactors should increase as their economics improve. Increases in construction and operation experience should reduce costs while increasing pressure on uranium resources may give fast reactors a fuel cost advantage over conventional thermal reactors.

To enable Sustained Recycle, the percentage of fast reactors will need to be between 80 percent and 100 percent. This evolution is expected to occur over several decades as commercial experience is gained with fast reactor construction and operation, with completion possible around 2100. Tightening of uranium ore supplies could accelerate this process. Uranium supplies are discussed in the next section.

To summarize, these results indicate that continuation of the current Once-Through fuel cycle would produce several hundred thousand metric tons of spent fuel this century under even conservative continuing nuclear energy scenarios; thus, nuclear waste disposal solutions will be required for sustained nuclear power. As an alternative to vastly-expanded permanent disposal space, the Transitional Recycle strategy can significantly improve the basic nature of nuclear waste disposal; further, the thermal load of the waste could be significantly reduced and the time-frame for waste isolation significantly altered.

The final stages of Transitional Recycle or Sustained Recycle, using Generation IV fast spectrum systems, offer the promise of managing all of the U.S. spent nuclear fuel produced throughout the twenty-first century so that no additional repositories would be required beyond a single facility.

Ultimately, market forces will determine:

- Whether evolution of the fuel cycle is required at all beyond the Once-Through stage;

- If so, the timing of the introduction of subsequent stages; and

- How far technology must advance along the "evolutionary scale" shown in Figure 1, in order to avoid additional repositories beyond the initial facility authorized by Congress.

To preserve maximum flexibility until the market appeal of commercial nuclear power increases and issues regarding resource use become clearer, and to begin as soon as possible to reduce the growth of weapons-usable material such as plutonium, it is recommended that research and development of reprocessing, transmutation fuels, and fast reactor technologies be completed in a timely manner. Rapid fielding of these technologies will be needed should domestic nuclear power plant construction resume. Analyses conducted to date suggest that major new AFCI research capabilities may need to be in place by 2015 to achieve timely demonstration of technologies at pilot- and engineering-scale prior to commercialization[7].

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7 Section 7 addresses the required capabilities more fully.

5 URANIUM RESOURCE ANALYSIS

An important objective of the AFCI program is to enhance energy security by improving the use of uranium resources. The urgency of this objective will be dependent upon the international market for uranium supply and demand. There are three major supply uncertainties – the size of conventional uranium resources, the increase in cost as conventional resources are used, and the practicality of unconventional uranium resources (such as sandstone deposits, phosphate deposits and sea water). Demand uncertainty is primarily driven by the rate of economic growth and the share of new energy to come from nuclear.

As directed by Congress, the Department in 2004 contracted for a study of global uranium reserves and global uranium demand[8]. The results of this study were compared to several other analyses of uranium supply and demand that have been conducted over the past several years, as reported in the *Generation IV Nuclear Energy Systems Roadmap* in 2002, the Massachusetts Institute of Technology (MIT) 2003 report *The Future of Nuclear Power*, the December 2003 report from Harvard University's Belfer Center, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*, and elsewhere[9]. All of these analyses interpreted resource data provided by the Organization for Economic Cooperation and Development (OECD) Nuclear Energy Agency (NEA)/International Atomic Energy Agency (IAEA) "Redbook", *Uranium 2003 (or earlier): Resources, Production and Demand.*

Figure 9 provides a summary of these multiple studies, indicating predicted retrievable uranium resources as a function of cost. (Footnote 9 identifies these studies.)

It is clear from these results that there is a high degree of uncertainty in the predictions of global uranium supplies, with little agreement from experts on even the method to be applied to estimate extractable reserves.

Global uranium demand is also highly uncertain. The United States has the largest installed base of nuclear reactors, and therefore forward predictions of U.S. uranium needs have the largest short-to-intermediate term impact on total demand. The Energy Information Administration's forward projection for U.S. nuclear output in 2020 has doubled in the last six years, due primarily to numerous license extensions. As for new growth, China has recently completed several new

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8 *Preliminary Assessment of Global Uranium Resources*, Energy Resources International Inc., ERI-2103-0501, January 2005.

9 Argonne National Laboratory Nuclear Engineering Division, *Dynamic Analysis of Nuclear Energy System Strategies (DANESS) v.1.07 Use's Manual.* Argonne, Illinois: February 2004.

Deffeyes, K. S. and I. D. MacGregor, "Uranium Distribution in Mined Deposits and in the Earth's Crust. Final Report," GJBX-1(79), Department of Geological and Geophysical Sciences, Princeton University, Princeton, NJ, Prepared for the DOE Grand Junction Office, August 1978.

Deffeyes, K. S. and I. D. MacGregor, "World Uranium Resources," Scientific American, 242, 1, 66-76, January 1980.

"Uranium 2003: Resources, Production and Demand," OECD Nuclear Energy Agency Report NEA-05291, June 2004. Earlier Redbooks are also available at http://www1.oecd.org/publications.

"Generation-IV Roadmap: Report of the Fuel Cycle Crosscut Group," US Department of Energy Report, March 2002. (FCCCG)

WNA info brief 75, http://www.world-nuclear.org/info/inf75.htm, August 2004.

Clarke, J. F., Edmonds, J., and C. Geffen, "Nuclear Technology Pathways to a Carbon-Neutral Energy System," Energy: The International Journal, under review.

reactors and announced plans for many more. At current growth rates, China will have more nuclear generating capacity than the United States later in this century.

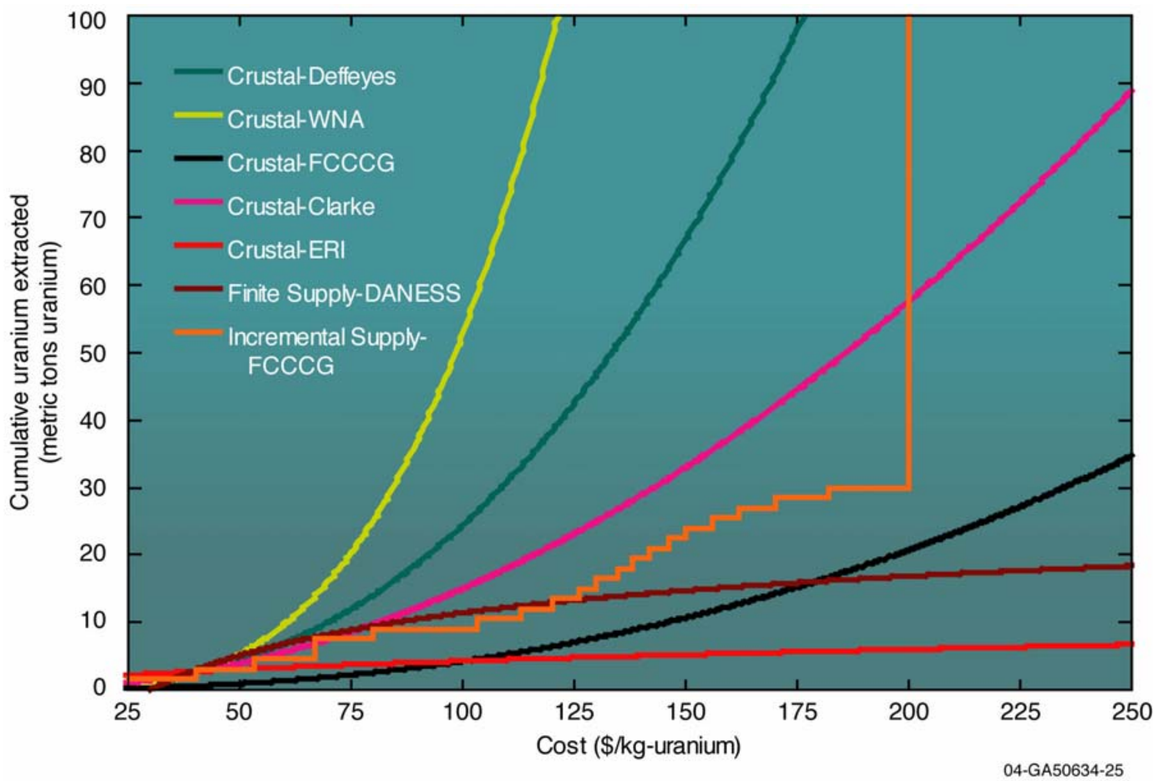

Figure 9. Comparison of uranium resource studies

China has also announced a fast reactor development program to provide technologies that will limit their long-term uranium needs.

The most troubling finding of the contracted uranium study was that new mines often take more than a decade from initial ore discovery before they are developed to the point of sustained ore extraction. In fact, many of the larger mines that have begun operation in the last 10 years are based on initial exploration efforts during the uranium boom of the 1960s and 1970s. Since the downturn of uranium prices of the 1980s, there has apparently been little incentive for additional exploration. Recently, prices have increased - but any new exploration stemming from these price increases will likely not result in additional operating mines until 2020 or beyond.

The AFCI planning basis is that uranium resources are not expected to be limiting for many decades under any of the analyzed growth scenarios, although short-term shortages may occur if low prices inhibit exploration and development of new mines. For the two growth scenarios evaluated, natural uranium supplies may become constrained toward the latter part of the century, especially if there is rapid international nuclear energy expansion. Under a rapid growth scenario, initial transition to Sustained Recycle would be needed late in the century to ensure adequate economical fuel supplies. Under slower growth scenarios or if unconventional uranium resources are shown to be practical, transition to Sustained Recycle could be deferred for one or more centuries (taking into account only a resource-consumption standpoint.) Increases in natural ore prices would assist in this transition by improving the economic competitiveness of fast reactors that are able to breed their own fuel versus thermal reactors that will continue to need an outside fuel supply. In Sustained Recycle, employing fast reactors to generate fuel from recycled uranium will achieve long-term energy security.

Because of the time lags involved, fast spectrum reactors would need to be deployed and operated as breeders before uranium ore resources become a problem. Figure 10 draws from the same studies as Figure 9 (see footnotes 8 and 9) and illustrates the impact of fast breeder reactor deployment on uranium resource needs. If the lowest estimate of conventional resources (known and recoverable) is true and nuclear growth occurs world-wide even at a conservative 1.8 percent per year, then full scale deployment of fast reactors is needed in 2020. Few experts believe that this lowest estimate (3,100,000 metric tons of uranium) is a good planning basis, in large part because there has been little exploration for uranium in the last several decades due to limited demand. If the highest current estimate of conventional uranium resources is true (16,000,000 metric tons of uranium), then full scale deployment of fast reactors can be deferred to around 2070. If extraction of unconventional resources is shown to be practical, deployment of fast reactors for fuel breeding could be deferred for two centuries or more.

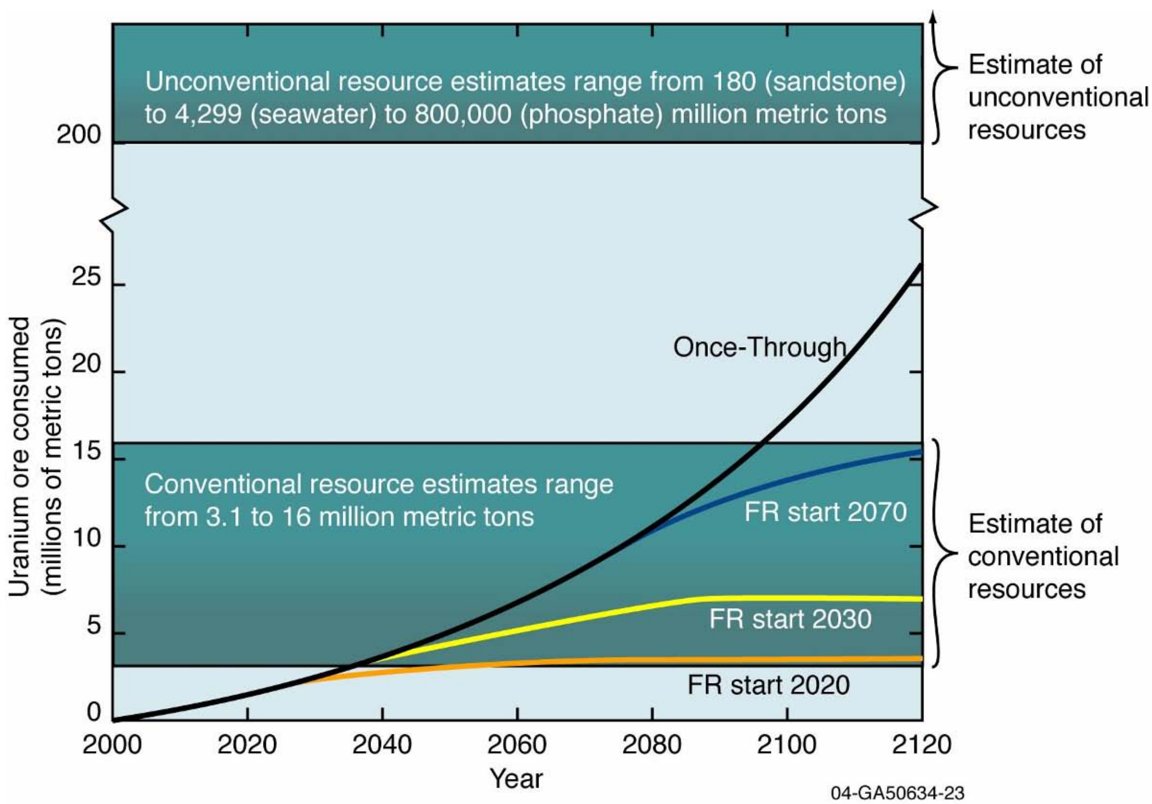

Figure 10. Impact of fast spectrum reactor (FR) deployment on uranium resource needs.

6 SUMMARY OF TECHNOLOGIES

6.1 Separations Technologies

The Limited, Transitional and Sustained Recycle fuel cycle stages discussed in Section 3 all require processing of spent nuclear fuel to separate re-usable materials for recycle from waste. The AFCI chemical separations technology development effort is directed toward:

- Providing a suite of separations methods to support the full range of fuel cycle options.

- Increasing the efficiency of separations to improve purity of separated materials and reduce processing losses to waste.

- Improving instrumentation and process designs to increase nonproliferation oversight and reduce facility size and costs.

The AFCI program is developing two types of separations processes, the first employing "aqueous" water-based methods and the second "dry" pyrochemical methods. The AFCI aqueous process is at an advanced stage of technological maturity and could be implemented at a commercial scale in the 2025-2030 time-frame for processing of LWR spent fuel. Pyrochemical methods are less mature and are directed principally toward the treatment of new types of spent fuel from Generation IV plants.

6.1.1 Aqueous Processing

<u>Overview</u>

France, the United Kingdom, and Russia practice aqueous processing of LWR spent fuel, and Japan will soon join this group. Each of these countries uses the Plutonium-Uranium Extraction (PUREX) process that produces three outputs – uranium, plutonium, and a waste stream containing the fission products and remaining transuranics. The AFCI program focuses its research and development on advanced aqueous separations, referring to processes that do not separate pure plutonium.

The following two subsections discuss the differences between the PUREX process and the AFCI approach to aqueous separations. Although the AFCI program, in compliance with the May 2001 *National Energy Policy* requirement to "continue to discourage the accumulation of separated plutonium, worldwide," will not separate pure plutonium, understanding the PUREX process is important as a benchmark against which to compare the development of various advanced separations technologies. Table 3 identifies some of the key distinctions between PUREX and advanced technologies.

<u>The Plutonium Extraction (PUREX) Process</u>

The PUREX process for treatment of spent nuclear fuel was developed more than 50 years ago. It has been used for both civilian and military purposes, and is based on the use of an organic solvent, tributyl phosphate (TBP), in an organic diluent.

Table 3. Comparison of various aqueous treatment processes for LWR spent fuel

	PUREX	Advanced Aqueous Separations		
		UREX (AFCI)	UREX+ (AFCI)	GANEX (France)
Process	• Extracts pure U and Pu, free from fission product contamination • Minor actinides go to waste along with fission products	Separates pure U • All transuranics are recovered as a group • Cesium and strontium removed to improve effective repository capacity • Lanthanide fission products can be retained with TRUs if needed to provide limited self-protection radiation barrier • Hybrid modification sends the process stream after U, Cs and Sr removal to a pyrochemical process for separation of TRUs from fission products for fast reactor recycle	• Several variants of the UREX process are being studied; all include separation of pure U and removal of Cs and Sr • Each variant provides different options for the recovery of transuranics, either as a group, or as subgroups, for use in different recycle scenarios in thermal and fast spectrum systems • Provides flexibility of response to evolving nuclear systems in the United States	• Bulk of U separated in pure form in first step • Remaining U and transuranics recovered as a group, together with lanthanide fission products • Lanthanides subsequently removed • No removal of cesium and strontium
Pure Pu separation	Yes	No	No	No
Remote fuel fabrication	No	Yes	Some variants would require remote fuel fabrication	Yes
Technology development completion	Commercially available now	2010	2012	2012
High-level waste (liquid) generation[1]	Large in old plants, very limited in modern operations	None	None	Very limited

[1] In the direct disposal case, the unpackaged volume of one ton of spent LWR fuel is about 1,100 liters

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PUREX is founded on the particular characteristics of uranium and plutonium nitrates for forming stable complex molecules with TBP. In the first stage of the PUREX process, both uranium and plutonium are extracted from nitric acid solution into the organic phase. This separates these two elements from the fission products and the minor actinides (americium, neptunium, curium). Subsequently, the plutonium is further reduced by addition of a reductant to the acid solution. The plutonium can then be separated efficiently, without uranium contamination. Finally, the uranium is stripped from the organic solution into the aqueous phase. The process is capable of producing separated streams of very pure uranium and plutonium.

In the early days of operation of PUREX, the high-level liquid wastes containing fission products and minor actinides were stored in underground waste tanks, creating a legacy waste disposal issue. More recently, as exemplified by the commercial spent fuel reprocessors in the United Kingdom, France and Japan, the liquid wastes have been sent to a vitrification plant where the wastes are immobilized in glass for final disposal. The volume of high-level waste produced has been reduced over the years, with the result that the amount of high-level waste per metric ton of spent fuel processed is now less than 0.25 cubic meter.

The PUREX process represents a proliferation concern due to its separation of very pure plutonium. There have been recent proposals to implement a “dirty PUREX” process whereby the decontamination of the plutonium product is incomplete. Of equal concern is the production of a high-level waste containing highly radiotoxic minor actinides, some of which are highly mobile in the geologic structure of the repository and some of which are prodigious heat generators through the process of radioactive decay. The presence of minor actinides in the waste stream from a PUREX process stimulated enactment of a French law in 1991 that mandated the study of means for their management. This study included assessment of separation and transmutation methods, and it is clear that the French program on advanced nuclear fuel cycles is converging with the AFCI approach. Other countries are also formulating programs along the same lines.

The AFCI Approach

Closure of the nuclear fuel cycle carries with it implications of the proliferation of nuclear weapons because it involves the recycle of usable fuel materials while they are being destroyed. Use of the PUREX process is not the preferred route for separating spent fuel components in the United States, but an advanced fuel cycle system would in any case involve the partitioning of spent nuclear fuel for recovery and recycle.

Selection of a particular fuel cycle closure method involves the choice of a chemical separations method and the choice of a recycle fuel type and associated fuel fabrication method. These choices must take into consideration the economic viability of a fuel cycle system as well as the proliferation resistance and physical protection afforded by candidate systems.

The uranium extraction plus (UREX+) approach being developed by the United States has the potential to reduce the costs of construction and operation of processing facilities by reducing (1) the amount of liquid waste requiring solidification and (2) the scale of processing equipment, such as process storage tanks, that must be included in plant design. Process storage has a major impact on overall facility costs because the storage tanks significantly increase the floor space required in the remote operations area at the core of the facility.

That evaluation must also consider the proposed deployment of the system, as regards both timing and location. If the system is intended only for domestic deployment in the United States, a nuclear weapons state, then the physical protection of materials in the fuel cycle becomes more important than the proliferation resistance aspects of the technology, especially, if the processes used are more complex and difficult to operate than the well-known PUREX technology. The timing of deployment of a more fully-closed nuclear fuel cycle is also important because reactor, fuels and separations technologies are advancing at a pace that will see major changes in these technologies within 20 to 25 years.

The proliferation resistance of a fuel cycle must be assessed for the whole system, not for a specific technology. Modern approaches for enhancing proliferation resistance include the possibility of tailoring the list of elements to be separated at each step, as allowed by both aqueous and pyrochemical processes, and also include the incorporation of proliferation resistance goals in the design of facilities and fuel cycle systems. These approaches will make the AFCI systems significantly more proliferation-resistant than currently-deployed PUREX-based fuel cycles.

High purity uranium oxide product recovered from spent LWR fuel in hot UREX+ process demonstration at Savannah River Site. No shielding is required for handling because the material is over 99.99 percent pure.

For these reasons, the development of AFCI separations and fuels technologies is proceeding as a broadly-based program. A suite of separations technologies is being developed, including both aqueous and non-aqueous processes. The aqueous processes are intended for the large-scale processing of spent LWR oxide fuel. UREX+ variations are at an advanced stage of laboratory scale feasibility demonstrations. All of the processes under evaluation incorporate a front-end step for the removal of uranium at a very high level of purity, permitting the disposal of the remaining spent fuel constituents in a manner more efficient and economical than direct spent fuel disposal. They also include a cesium/strontium extraction step for removal of radionuclides producing the short-term decay heat load in spent fuel. The development of these aqueous processes, which will require an extended period of research, development and demonstration, will provide the United States with appropriate options when and if a decision is made to proceed with Limited Recycle or Transitional Recycle.

6.1.2 Pyrochemical Processing

Pyrochemical processing is an alternative to aqueous processing, particularly in the case of the treatment of Generation IV fuels, which are likely to be distinctly different from conventional LWR oxide fuel. Many of the fuel types being considered for the Generation IV reactors are not compatible with conventional aqueous processing. They include ceramic-ceramic and ceramic-metal fuels, certain metal alloy fuels, and mixed nitride and carbide fuels. The pyrochemical process being developed under the AFCI program does not produce a separation of the actinide elements: all transuranic elements are recovered together, along with a significant fraction of the uranium present in the spent fuel. Pyrochemical processing is carried out in a batch manner which confers the benefit of simplified material accountability and transparency.

Pyrochemical processing development efforts benefit greatly from the experience gained in domestic treatment of spent fuel from the Experimental Breeder Reactor-II (EBR-II) fast reactor. Spent fuel treatment has been carried out in facilities with equipment that is capable of sustaining a throughput of up to five metric tons per year. In this process, the spent fuel is dissolved in molten salt, and the uranium is separated electrically. With the current fuel treatment process, the transuranic elements are left in the waste. However, testing has confirmed that group recovery of transuranic elements and uranium may be feasible by testing on a kilogram scale. Group transuranic recovery may be carried out in two ways. The first involves the use a modified cathode in the existing process equipment, while the second is based on electrolysis of the salt recovered from the pyrochemical fuel treatment. In either case, the chemical properties of uranium and the transuranic elements dictate recovery of a mixed uranium/transuranic product.

This specific process would be most applicable for processing metallic and nitride fuel forms. An electrochemical reduction front-end step would also make the process applicable to oxide and oxycarbide fuel types. Development of this head-end process is underway and tests with irradiated oxide fuel showed that uranium oxide can be readily reduced to the metallic state. Research efforts are focusing on evaluating the impact of fission products on the reduction process.

The PYROX process, a pyrochemical process for the treatment of spent oxide fuel, could be used for treatment of LWR spent fuel if applied in small scale, co-located plants, where it is expected to be cost-effective. PYROX, however, has not been shown to be efficient in the removal of certain rare earth elements and thus may preclude the use of the separated fuel materials in recycle to LWRs. Further analysis is needed to assess the impacts of rare earth contamination on fuel destined for recycle in LWRs. Still, the process may be applied for recycle of separated fuel materials to fast spectrum reactors, where the sensitivity to rare earths is much less. Pyrochemical processes are being developed for the treatment of metallic, nitride and carbide fuels and appear to be very effective in those applications.

6.1.3 Future Reprocessing Plant Design for Proliferation Resistance and Physical Protection

In the changing world since September 11, 2001, it is imperative that all means at the disposal of the technical community be brought to bear on assuring the protection of nuclear materials. The development of fuel cycle technologies under AFCI is receiving increased emphasis on materials protection, control and accountancy. The development of these advanced technologies represents a significant departure from the PUREX process and its attendant proliferation concerns. The United States is in the position of being able to design new plants for future spent fuel processing and recycle fuel fabrication, with a comparatively large window of time in which to incorporate advanced technologies into these designs.

One of the tenets of current design thinking is the co-location of a chemical separations plant with the recycle fuel fabrication plant, to minimize the transport of separated nuclear materials. In addition, work is accelerating, in collaboration with the DOE National Nuclear Security

Administration, the national laboratories, industry and universities, on the development of advanced instrumentation methods for process monitoring and control, with the goal of developing precision instruments that can provide on-line, real-time precise measurements of the fissile material content of process streams and product forms. The presence of small amounts of neptunium and americium and even curium in the recycle fuel product streams offers the ability to measure quantitatively the ratios of easily-detectable isotopes such as plutonium-238, neptunium-237, neptunium-239 and americium-243, thereby providing a ready indication of any diversion of weapons-usable materials.

A major component of the proliferation resistance objective is the development of advanced materials protection, control and accountancy technologies that can be implemented in future plant designs and set a new standard for the physical protection of sensitive materials against diversion or terrorist action. This, if implemented by the United States, would provide a standard against which all future treatment in the world could be measured and establish a position of leadership in the nuclear fuel cycle that the United States does not presently enjoy.

Even if UREX+ or some other variety of aqueous reprocessing should prove unable to fulfill the promise it currently appears to offer, there remain good reasons to continue to research and develop aqueous separations technologies. For example, without aqueous reprocessing, the United States will lack a domestic technology to transition from thermal to fast reactors. The AFCI program will also be unable to benefit the geologic repository prior to the commercial deployment of fast reactors.

6.1.4 Waste Forms

Another important element of the separations technology development effort is the development of product and waste storage forms that can be produced at reasonable cost and that exhibit the level of durability required for their ultimate disposition. Storage/disposal forms are being developed for uranium, cesium/strontium, iodine/technetium, plutonium/neptunium, and americium/curium (either together with plutonium/neptunium or separate), so that a complete technology package can be available for use. The high-level waste forms that will result from advanced chemical separations are intended to be compact in volume and significantly more durable than the spent fuel from which the waste materials are derived. This research has applications to other DOE programs such as those involving closure of storage tanks for high level radioactive waste.

6.2 Fuel Technologies

The AFCI program is investigating alternate fuel forms for recycle of transuranics in conventional LWRs and advanced LWRs. Mixed oxide fuels containing various combinations of the transuranic elements neptunium, plutonium, americium, and curium are being assessed. Inert fuel matrices, or uranium-free fuel forms, are also being investigated to further improve transuranic management. The development of these inert matrix fuel forms is less mature than the mixed oxide fuel forms, but offers the potential to reduce the overall inventory of actinides.

The Very High Temperature (Gas) Reactor (VHTR) concept is a key focus of the current U.S. Generation IV program. The AFCI program is developing fuels for the VHTR. The current VHTR concept uses an enriched uranium particle fuel embedded in a graphite matrix. AFCI is developing processes for the manufacture of this new fuel type. The program is also considering advanced uranium-free VHTR fuel for transmutation.

Fast reactor technologies have been developed in many countries, including the United States, France, Germany, India, Japan, and Russia. Fast reactors were originally conceived as breeders, designed to transmute uranium to create more fissile material to start new reactors. In the breeder design, large amounts of uranium are placed in the reactor to absorb neutrons and then processed to separate the fissile material. Recent international studies have explored the development of "burner" or transmuter designs for weapons plutonium disposition and reducing environmental impacts. In a burner design, the non-fuel uranium is left out, resulting in more transuranics being destroyed than created. In recent AFCI studies, deep burner designs have been assessed and their safety behavior analyzed. Uranium-free fuel forms have also been considered for dedicated burner reactor and sub-critical accelerator applications.

The effectiveness of fast spectrum systems for transuranics transmutation has been well documented. AFCI Transitional Recycle and Sustained Recycle approaches both employ fast reactors. However, it may be more cost effective and timely to consume transuranics in advanced LWRs for the early recycles when the fissile content is still high. Deployment of the Limited Recycle approach will provide near-term benefit while allowing a gradual transition into Generation IV fast reactor concepts as they become available. It will also allow time to develop an experience base to improve fast reactor economics before larger numbers are built.

7 KEY RESEARCH CAPABILITIES

Below is a list of research capabilities that the AFCI program believes would be beneficial in supporting key research on fuel cycle technologies. The AFCI program recognizes that funding support for these capabilities will fall within a fiscally responsible budgetary envelope and will be contingent on many factors. These research capabilities include:

- Larger-scale research on reprocessing technologies, including scalability tests of different separations methods and proof testing of monitoring and material accountability methods;

- Feed material for scale-up fuels research;

- Larger-scale remote fuel fabrication to support advanced fuels development and qualification;

- Improved irradiation capabilities to accommodate up to full-size fuel assemblies for fuels testing of both conventional and Generation IV fuels;

- Upgraded and up-to-date hot cells for post-irradiation examination of fuels and materials.

- Small- to engineering-scale development and demonstration of advanced transmutation processing technologies;

- Small- to engineering-scale development and demonstration of real-time materials control and accountability for greatly-improved proliferation-resistant spent fuel treatment and fuel fabrication technologies; and

- Small- to engineering-scale development and demonstration of zero-emission operation.

These capabilities would support both aqueous and pyrochemical separations process development, with small hot cells for unit operations testing and larger hot cells for integrated process evaluation. Co-location of fuel fabrication activities would support engineering-scale testing of advanced fabrication technologies for LWR and Generation IV reactor fuels.

Additionally, adequate laboratory capability would help to develop and test advanced transmutation fuel cycles for existing and Generation III+ LWRs, Generation IV reactors, and those fuel cycles that would be used in transitioning from Generation II and III to Generation IV reactors.

7.1 Advanced Reprocessing and Fuel Fabrication Capabilities

AFCI analyses identified the benefit of a large-scale commercially-deployed separations plant, ideally with co-located fuel fabrication facilities, by 2025. The AFCI program envisions pilot-scale separations research capabilities to support this commercial facility in place by 2015.

The initial design studies have identified beneficial capabilities for the development and demonstration of spent fuel processing methods applicable to current LWR fuels and for fuels used in future thermal and future fast reactors (including oxide, metal, and nitride fuels). A capability for fuel fabrication development would also prove helpful, including fuels for thermal reactor recycle (both mixed oxide fuels and inert matrix fuels) and Generation IV reactor fuels.

Incorporated in these laboratories would be a capability for the development and demonstration of state-of-the-art instrumentation for process control and materials accountability.

To facilitate the effective use of scalable research activities over a period of several decades, the main hot cells could be designed to use drop-in equipment modules with individual containment to limit the spread of contamination and maximize flexibility for testing of advanced processes and systems.

Although priorities could change, the separations research capabilities would be followed by remote fuel fabrication capabilities and a few years later with Generation IV reactor fuels research capabilities.

7.2 Fuel Irradiation and Materials Testing Capabilities

Irradiation activities would be used to test recycle fuels for both conventional and fast spectrum reactor systems. The capability to conduct these tests would be conducted concurrently with a remote fuel fabrication capability for new recycle fuel types. However, with the shutdown of EBR-II and the Fast Flux Test Facility in the early 1990s, the United States has no broad-spectrum irradiation facilities for testing fast neutron spectrum fuel cycle and reactor concepts.

Testing is currently done in the United States in the Advanced Test Reactor (ATR) in Idaho, which provides a thermal neutron spectrum. A fast flux booster is currently being considered in the design of a gas test loop at ATR. However, the loop’s small test volume will only accommodate tests with a few rods, encapsulated pellets, or small sub-assembly sized experiments. Large-scale prototypic tests of full-length fuel assemblies would be used to qualify advanced fuels for Generation IV fast reactors.

Fast neutron spectrum transmutation fuel test facilities are available overseas, and the AFCI program is collaborating with other countries to conduct fuel tests in the Phénix reactor in France and the JOYO reactor in Japan. After the planned shutdown of the Phénix reactor in 2008, the JOYO and perhaps BOR60 in Russia will be the only fast spectrum facilities available worldwide in which to perform the necessary tests. If restarted, the MONJU reactor in Japan may also become available. Having a domestic reactor of this nature would streamline research logistics and avoid problems associated with overseas shipments of nuclear materials.

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Appendix A

Energy and Water Appropriations Congressional Language

(Highlights Added)

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108TH CONGRESS
1st Session
HOUSE OF REPRESENTATIVES
REPORT
108–357

MAKING APPROPRIATIONS FOR ENERGY AND WATER DEVELOPMENT FOR THE FISCAL YEAR ENDING SEPTEMBER 30, 2004, AND FOR OTHER PURPOSES

NOVEMBER 7, 2003.—Ordered to be printed

Mr. HOBSON, from the committee of conference, submitted the following

CONFERENCE REPORT

[To accompany H.R. 2754]

The committee of conference on the disagreeing votes of the two Houses on the amendment of the Senate to the bill (H.R. 2754) "making appropriations for energy and water development for the fiscal year ending September 30, 2004, and for other purposes", having met, after full and free conference, have agreed to recommend and do recommend to their respective Houses as follows:

That the House recede from its disagreement to the amendment of the Senate, and agree to the same with an amendment, as follows:

In lieu of the matter stricken and inserted by said amendment, insert:

That the following sums are appropriated, out of any money in the Treasury not otherwise appropriated, for the fiscal year ending September 30, 2004, for energy and water development, and for other purposes, namely:

TITLE I

DEPARTMENT OF DEFENSE—CIVIL

DEPARTMENT OF THE ARMY

CORPS OF ENGINEERS—CIVIL

The following appropriations shall be expended under the direction of the Secretary of the Army and the supervision of the Chief of Engineers for authorized civil functions of the Department of the

90–306

The conference agreement includes $3,000,000 for the Navajo electrification demonstration program; $1,000,000 to continue development of the bipolar nickel metal hydride battery storage system; $250,000 for the Microgrid distributed generation prototype in Vermont; $500,000 for the Natural Energy Laboratory in Hawaii to continue development and deployment of distributed energy systems; $2,000,000 for research, development, and demonstration of advanced thermal energy storage technology integrated with renewable thermal energy technology; and $400,000 for the Diné Power Authority.

NUCLEAR ENERGY

The conference agreement provides $300,763,000 for nuclear energy activities instead of $268,016,000 as proposed by the House and $437,422,000 as proposed by the Senate. The conference agreement does not include language specifying funding allocations as contained in the House and Senate reports. With the designation of the Office of Nuclear Energy, Science and Technology as the lead office with landlord responsibilities for the Idaho site, $112,306,000 of costs are allocated to the 050 budget function and are funded in the Other Defense Activities account. The Department should follow this structure in its fiscal year 2005 budget submission.

Radiological Facilities Management.—The Office of Nuclear Energy, Science and Technology operates a variety of facilities and equipment to support the needs of space, defense, and medical customers who obtain radiological materials from the Department of Energy on a reimbursable basis.

Space and defense power systems infrastructure.—The conference agreement includes $36,230,000 to maintain the infrastructure necessary to support future national security needs and National Aeronautics and Space Administration missions.

Medical isotopes infrastructure.—The conference agreement includes $28,425,000 for the medical isotope program. From within available funds, the Department is directed to provide $4,000,000 for upgrades of radiological facilities at Oak Ridge National Laboratory.

University reactor fuel assistance and support.—The conference agreement includes $23,500,000, an increase of $5,000,000 over the budget request. The conferees provide an additional $2,500,000 to fund more regional university reactor consortia, and the conferees strongly encourage the Department to request sufficient funding in future years to fund all meritorious proposals. The conferees also provide an additional $2,500,000 to pay for the university costs of transporting spent nuclear fuel from university reactors. The conferees encourage the Department to support the new graduate program in nuclear engineering at the University of South Carolina and the new program being considered at the University of Nevada-Las Vegas.

Research and development.—The conference agreement provides $132,500,000 for nuclear energy research and development activities, an increase of $5,475,000 over the budget request. The conference agreement includes $3,000,000 for nuclear energy plant optimization (NEPO), $11,000,000 for the nuclear energy research initiative (NERI), $44,000,000 for nuclear energy technologies,

$6,500,000 for the nuclear hydrogen initiative, and $68,000,000 for the Advanced Fuel Cycle Initiative (AFCI).

Within the funds provided for NEPO, the conferees include $1,000,000 to expand the transfer of the Mechanical Stress Improvement Process (MSIP) technology to other countries in the former Soviet Union.

Of the $44,000,000 made available for nuclear energy technologies, $20,000,000 is for Nuclear Power 2010 and $24,000,000 is for the Generation IV initiative. The Department is directed to use $15,000,000 provided under the Generation IV initiative to begin the research, development, and design work for an advanced reactor hydrogen co-generation project at Idaho National Laboratory.

The $6,500,000 made available for the nuclear hydrogen initiative includes $2,000,000 to support research and development on high temperature electrolysis and sulfur-iodine thermochemical technologies necessary to support the advanced reactor hydrogen co-generation project at Idaho National Laboratory, and $2,000,000 for the University of Nevada-Las Vegas Research Foundation to continue the development, in partnership with industry and national laboratories, of an efficient high temperature heat exchanger.

Within the funds available for AFCI, the conference agreement includes $2,000,000 for the Idaho Accelerator Center; $3,500,000 for the University of Nevada-Las Vegas; and $3,000,000 for directed research aimed at enhancing university-based collaborations on AFCI. The conferees also direct the Secretary to conduct the study, described in more detail in the Senate report, to identify the necessary capacities and time scales for implementation of advanced recycle technologies, and to report to Congress by March 2005 with quantitative goals for the AFCI work. The conferees expect the Department to partner with universities and industry, as well as use existing expertise at national laboratories, in this effort.

Idaho Facilities Management.—The conference agreement provides $42,615,000 for ANL–West operations, including an additional $5,000,000 for the addition of a high temperature gas loop in the Advanced Test Reactor and $6,000,000 for deferred landlord activities and critical infrastructure needs. The conference agreement provides $31,605,000 for infrastructure at the Idaho National Engineering and Environmental Laboratory (INEEL), of which $21,415,000 is allocated to the 050 budget function. The conference agreement provides the requested amounts of $500,000 for project 95–E–201 and $1,840,000 for project 99–E–200, both at the Test Reactor Area.

Idaho Sitewide Safeguards and Security.—The conference agreement provides $56,654,000 for Idaho sitewide safeguards and security. Consistent with the request, all of these costs are assigned to the 050 budget function.

Program direction.—The conference agreement includes $59,200,000 for program direction. Of this amount, $34,815,000 is assigned to the 050 budget function.

Funding adjustments.—The conferees direct the Department to use $20,000,000 of prior year funds to meet a portion of the Department's liability stemming from the termination of the contract with the Ohio Valley Electric Corporation for power to supply the Ports-

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Calendar No. 213

108TH CONGRESS *1st Session*	SENATE	REPORT 108–105

ENERGY AND WATER DEVELOPMENT APPROPRIATION BILL, 2004

JULY 17, 2003.—Ordered to be printed

Mr. DOMENICI, from the Committee on Appropriations, submitted the following

REPORT

[To accompany S. 1424]

The Committee on Appropriations reports the bill (S. 1424) making appropriations for energy and water development for the fiscal year ending September 30, 2004, and for other purposes, favorably thereon and recommends that the bill do pass.

Amount in new budget (obligational) authority, fiscal year 2004

Budget estimates considered by Senate	$26,946,164,000
Amount of bill as reported to the Senate	27,313,000,000
The bill as reported to the Senate—	
Above the budget estimate, 2004	1,236,805,000
Over enacted bill, 2003	366,836,000

88–359 PDF

resources to begin the research, development and design phase of an advanced reactor hydrogen co-generation project at Idaho National Laboratory.

The Committee remains interested in the potential use and application of small modular reactors that would be inherently safe, be relatively cost effective, contain intrinsic design features which would deter sabotage or diversion, require infrequent refuelings, and be primarily factory constructed and deliverable to remote sites. The Department shall continue to support the international effort to develop this technology.

The recommendation does not include the requested funding for the national climate change technology initiative.

Nuclear Hydrogen Initiative.—The Committee recommendation includes $8,000,000, an increase of $4,000,000 over the request. The additional funding is provided to support research and development necessary to support-high-temperature electrolysis and sulfur-iodine thermochemical technologies necessary to the advanced reactor hydrogen co-generation project at Idaho National Laboratory. Additionally, the recommendation includes $2,000,000 to continue the development, in partnership with industry and national laboratories, of an efficient high temperature heat exchanger at the University of Nevada-Las Vegas. These funds shall be provided to the UNLV Research Foundation.

Advanced Fuel Cycle Initiative.—The Committee recommendation includes $78,025,000, an increase of $15,000,000 over the budget request. The initiative should continue to focus on development of fuel cycle technologies that minimize the toxicity of final waste products resulting from spent fuel while recovering energy remaining in spent fuel; maximizing the utility of the Yucca Mountain repository, consistent with statutory limits on its contents, or any future repository; and minimizing proliferation concerns and environmental impacts of the fuel cycle. The initiative shall assist the Secretary with development of alternative technology options that may influence the Secretary's 2007 statutorily required recommendation for the need to develop a second repository.

The Committee notes that the January 2003 Report to Congress on this project focused primarily on use or modification of existing reprocessing technologies. The Committee directs that the Department shall also explore new and alternative approaches to provide high confidence that the options finally chosen are the best for further development. The Department shall also contract for studies to determine the probable extent of global uranium reserves and global uranium demand. Based on these studies, and on a range of assumptions about the available capacity of monitored retrievable storage and repositories in the country, the project shall identify time scales on which elements of an advanced fuel cycle must be operational in order to impact national requirements for management of spent fuel. This study should include information to guide Congress in establishing the date by which an advanced recycle facility must be available for performing research on scalable, proliferation resistant, waste efficient, recycle technologies as well as other key facilities supporting future spent fuel management strategies. Based on these studies, the Secretary is directed to report to Congress by March 2005 with quantitative goals for the program including evaluation of future spent fuel inventories, and detailed analysis of the various options to achieve these goals.

To provide confidence in the technology options proposed, the project will use Department of Energy national laboratory and University expertise to perform research and development of advanced technologies for spent fuel treatment and transmutation of plutonium, higher actinides and long-lived fission products. Advanced nuclear material recycle and safeguard technologies, proliferation-resistant nuclear fuels, and transmutation systems shall be investigated. Both reactor-based and a combination of reactor and accelerator-based transmutation approaches may be included as part of the research and systems analysis.

The project shall use international and university collaborations to provide cost effective use of research funding. Within the funds made available for this initiative, $1,500,000 is provided for the Idaho Accelerator Center, $4,500,000 for the University of Nevada Las Vegas, and $3,000,000 for directed research aimed at enhancing university-based collaborations focused on the Advanced Fuel Cycle Initiative with U.S. universities. All university research shall be closely coordinated with the technical projects conducted by principal investigators within the national laboratories.

IDAHO FACILITIES MANAGEMENT

The Committee recommendation includes $78,160,000, an increase of $12,600,000 over the request. The recommendation includes an additional $6,000,000 for the addition of a high-temperature gas loop in the Advanced Test Reactor, and an additional $6,600,000 for deferred landlord activities including the development of a remote treatment facility to treat remote-handled transuranic waste, remediation of an industrial waste pond, and to address other critical infrastructure issues.

PROGRAM DIRECTION

The Committee recommendation includes $60,207,000 for program direction, the amount of the request.

ENVIRONMENT, SAFETY, AND HEALTH

Appropriations, 2003	$22,553,000
Budget estimate, 2004	30,000,000
Committee recommendation	22,437,000

The Committee recommendation includes $22,437,000 for non-defense environment, safety, and health which includes $15,641,000 for program direction.

ENERGY SUPPLY INFRASTRUCTURE

Appropriations, 2003	$0
Budget estimate, 2004	0
Committee recommendation	17,600,000

The Committee recommendation provides $17,600,000 for energy supply infrastructure.

The Energy Supply Infrastructure program provides assistance, technical support, and project funding to specific energy projects. The Committee recommendation includes $2,000,000 for the Upper